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Effect of Humidity Ratio on Corn Moisture Content as Determined by the Air-Oven

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ABSTRACT

Shelled corn was oven dried at 103° C for 72 h with air having dew point temperatures of 9, 13, 18, 24, and 29° C. An additional test was performed with desiccant-dried air. Measured values of air-oven corn moisture content (superficial corn moisture content) dropped by as much as 0.9 percentage points (dry basis) as a result of increases in humidity ratio of the drying air. The amount of moisture left in the corn samples at the conclusion of the 72-h drying period, the apparent final moisture content, was found to be a quadratic function of humidity ratio.

INTRODUCTION

The air-oven drying method is the primary standard for determination of moisture content of grain and seed. The ASAE procedure for corn specifies that whole kernels be dried in a forced-convection oven at an air temperature of 103° C for a 72-h period (ASAE, 1987). As a primary standard, the air-oven method is used for calibration of secondary standards. The various techniques which measure moisture-related electrical properties of grain (such as capacitance or resistance) are examples of secondary standards. The air-oven procedure is also widely used in research. In all applications, accuracy and reproducibility are of primary importance. Research concerning the accuracy of the air-oven method has included subjects such as: quantification of loss of nonaqueous volatiles (Hart, 1972); inaccuracies that result from the weighing of heated samples (Taraba, 1979); and effects of sample weight and drying time (Sitzmann, 1980). Some research has focused on the calibration of electronic meters with the air-oven method (Hurburgh et al., 1985, 1987).

Little information is available concerning the influence of ambient air conditions on the accuracy of the air-oven method. The 72-h, 103° C air-oven procedure for whole corn was designed to yield corn moisture contents that closely correspond to those found by the Karl Fischer method (Hart et al., 1959). Hunt and Pixton (1974) note that corn dried in an oven at 103° C experiences an average nonaqueous loss of 0.34%. This loss was found to occur during the early stages of drying when the corn was heating up to the temperature of the oven. Hunt and Pixton (1974) explain that the 72-h, 103° C air-oven procedure was chosen so that about 0.3% moisture is left in the sample to offset the nonaqueous losses. Since the nonaqueous losses and the 0.3% final moisture content of the corn sample approximately cancel one another, the "apparent" final moisture content is zero. It is assumed that this apparent final moisture content is obtained regardless of the air humidity. If, however, the apparent final moisture content of corn dried at 103° C is not a constant value of zero over a range of air humidities, then the resulting errors should be quantified.

Suspected errors were observed by the third author in oven moisture tests performed at Iowa State University. The variation was correlated with relative humidities recorded during the tests. For corn samples of similar wetness, the measured values of moisture content, the "superficial" corn moisture values, were lower on days when the ambient air humidity was high. This suggested that drying was incomplete; the final moisture content of the oven-dried corn samples exceeded the value of 0.3% indicated by Hunt and Pixton (1974). Nonaqueous losses were less than the amount of water retained. Hence, the apparent final moisture content was greater than zero.

Objectives

The overall objective of this study was to examine the influence of air humidity on the values of corn moisture content obtained by use of the standard ASAE air-oven procedure (ASAE, 1987). Specific objectives were

1. To demonstrate the dependence of superficial corn moisture content on the humidity ratio of the drying air.
2. To characterize the relationship between apparent final moisture content of the corn and humidity ratio of the drying air.

EXPERIMENT

An apparent final moisture content for oven-dried corn that is a function of air humidity would cause calculated corn moisture content, the superficial corn moisture content, to deviate from "true" values obtained by either the Karl Fischer method or the standard ASAE procedure (ASAE, 1987) with the corn dried to an apparent final moisture content of zero. For convenience, corn moisture contents determined for apparent final moisture contents of zero will henceforth be referred to as "actual" moisture contents. To quantify the relationship between apparent final moisture

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content, superficial corn moisture content, and actual moisture content, the following variables were defined:

DWO = "actual" dry weight of corn sample (grams), that is, dry weight of corn sample for an apparent final moisture content of zero
MCO = actual moisture content (% db)
X = apparent final moisture content (% db) of corn sample
MCX = superficial corn moisture content (% db), that is, the value of moisture content indicated by the air-oven method for corn dried to an apparent final moisture content, X
DWX = measured or "superficial" dry weight of sample (grams) for corn dried to an apparent final moisture content, X
WET = wet weight of sample (grams)
W = humidity ratio of drying air (grams water per gram dry air)

When apparent final moisture content is X, the relationship between DWX and DWO is given by

$$DWX = DW0 * (100 + X)/100 \quad [1]$$

The moisture content relationships are expressed in equations [2] and [3]

$$MCX = 100 * (WET - DWX)/DWX \quad [2]$$

$$MC0 = 100 * (WET - DW0)/DW0 \quad [3]$$

Manipulating [1], substituting into [3], and rearranging yields

$$MC0 = (100 + X)*WET/DWX - 100 \quad [3a]$$

Expansion of equation [3a], use of equation [2], and additional manipulation yield the identity expressed in equation [4]

$$MC0 = MCX + X * (MCX + 100)/100 \quad [4]$$

Equilibrium moisture contents of hygroscopic substances such as corn are functions of air temperature and relative humidity (Henderson and Perry, 1976). The concept of apparent final moisture content for corn dried in an air-oven is distinctly different from equilibrium moisture content, but one might expect that apparent final moisture content is also related to air (oven) temperature and relative humidity. Barometric pressure could conceivably have some effect, but is assumed to be relatively constant. Thus, the atmospheric factors most likely to affect apparent final moisture content would be temperature and relative humidity. Because oven temperature is maintained at 103° C, relative humidity is the only **atmospheric** variable that might affect the apparent final moisture content, X, of oven-dried corn. It is not convenient to measure relative humidity of air in an oven, however.

At any given temperature, 103° C for example, relative humidity can be directly related to humidity ratio, W. The advantage of measuring humidity ratio, which is independent of temperature, is that the humidity ratio of air in the oven approaches the humidity ratio of the ambient air as the samples dry, and the evaporated moisture is exhausted from the oven. Thus, for corn dried in an air-oven, the apparent final moisture content, X, can be considered a function of the humidity ratio, W, of the ambient air. It is relatively simple to determine the humidity ratio of ambient air.

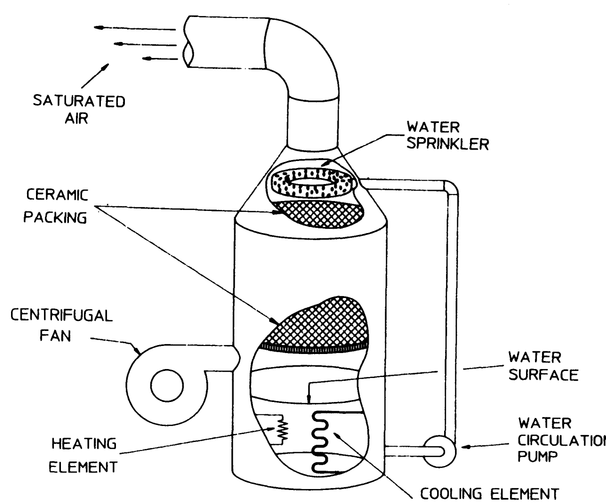

Fig. 1—Tower used to saturate air at selected temperatures.

Equipment

A forced-convection oven was modified so that all air admitted to the oven first passed through a saturation tower in which the air was saturated at a specific temperature. Figure 1 shows the components of the saturation tower. At the bottom of the tower, a reservoir of water was maintained at a selected temperature. A fan forced air into the chamber just above the water surface, then up through a layer of ceramic packing located approximately 10 cm above the water. The water, circulated by a pump, drained down through the ceramic packing and back to the reservoir. Above the packing, air, saturated at the temperature of the water, was ducted to the oven plenum. From plenum, the air entered the oven chamber and was eventually expelled through two exhaust ports at the top of the oven.

Thermocouples were used to monitor temperatures in the water reservoir, in the air collection cowl at the top of the saturation tower, and in the oven plenum. A small positive pressure was maintained in the oven plenum and in the ducts between the saturation tower and the oven. Static pressure in the saturation tower between the water surface and the ceramic packing was 2.3 mm water. The air flow rate, 0.006 1 m^3/s, was estimated from the fan performance curve.

Procedure

The ASAE standard air-oven procedure was used (ASAE, 1987). Shelled corn samples weighing 15 g were dried at 103° C for 72 h. For the initial tests, three lots of corn were tested at three dew point temperatures: 9, 13, and 24° C. From each lot of corn, five samples were drawn for moisture analysis at each of the three dew point temperatures. For a fourth lot of corn, moisture contents were measured at dew point temperatures of 9, 13, 18, 24, and 29° C. There were no differences, other than moisture level, among the lots of corn. Lot 4 was collected approximately six months later than lots 1, 2, and 3, however.

The fourth lot of corn was first tested at the 29° C dew point temperature with five replications. Ten replications were used for the remaining temperatures. At the 18° C dew point temperature, two samples were lost due to spillage. One test on the fourth lot was performed with the air dried by filtration through a column containing 900-1 000 g of the desiccant, magnesium perchlorate. To maintain its moisture absorbing capacity, the desiccant was changed twice during the test. The desiccant-dried air was assumed to have a humidity ratio of zero; hygrometer readings verified this assumption.

RESULTS

Analysis of Data

Statistics summarizing the data from all tests appear in Table 1. Since test procedures and equipment were identical for all four lots of corn, the relatively larger values of sample standard deviation for the moisture contents of lot 4 can only be explained by higher moisture variability of the corn from which lot 4 was drawn.

Least-squares regression was used to test for a significant effect of humidity ratio, W, on superficial corn moisture content:

$$MCX = BO + B1 * W$$

If the slope, B1, is different from zero, then a significant linear effect of humidity ratio is suggested. A linear effect (P=0.05) was found for all four lots of corn. Statistics for these models are summarized in Table 2.

Note that the regression equations obtained by this approach are unique for each corn lot. A general expression for apparent final moisture content as a function of humidity ratio is needed. Rearranging equation [4]

$$MCX = MC0 - X * (MCX + 100)/100 \quad \ldots\ldots\ldots\ldots [5]$$

Next, assume that apparent final moisture content equals zero when humidity ratio equals zero. The unknowns in equation [5] are MCO, the actual moisture content, and X, the apparent final moisture content. By using the data summarized in Table 1, a system of 88 linear equations with 9 unknowns can be obtained (MCO values for lots 1, 2, 3, and 4 and X values for the five nonzero absolute humidities). Least squares regression yielded MCO values for lots 1, 2, 3, and 4 of 15.67, 19.553, 23.599, and 20.530 (% db), respectively.

Apparent final moisture contents corresponding to humidity ratios of 0.0, 0.007 0, 0.009 2, 0.013 3, 0.018 8, and 0.026 4 (g water/g dry air) were 0.0, −0.551 9, 0.039 49, 0.065 94, 0.265 9, and 0.471 2 (% db), respectively. The negative value for apparent final moisture content at humidity ratio 0.0070 was considered an outlier. When the data for humidity ratio 0.0070 were omitted, recalculated estimates of MCO and X at the remaining five humidity ratios were extremely close to their previous values and are listed in Table 3. These values, obtained by use of equation [5], represented the data with an R-square of 0.992. The apparent final moisture contents for humidity ratios

TABLE 1. Superficial corn moisture contents as determined by the air-oven method for various drying air humidity ratios

Lot	Dew Point Temperature °C	Humidity Ratio (g water/g dry air)	Number of Observations	Calculated moisture content, % dry basis: Mean	Standard Deviation	Range
1	9	0.007 0	5	16.343	0.126	0.272
1	13	0.009 2	5	15.555	0.048	0.099
1	24	0.018 8	5	15.400	0.064	0.159
2	9	0.007 0	5	19.239	0.199	0.526
2	13	0.009 2	5	18.431	0.063	0.046
2	24	0.018 8	5	18.301	0.138	0.114
3	9	0.007 0	5	24.242	0.134	0.277
3	13	0 009 2	5	23.438	0.176	0.408
3	24	0.188	5	23.426	0.208	0.505
4	dessicant dried	0.000	10	20.534	0.271	0.765
4	13	0.009 2	10	20.612	0.192	0.562
4	18	0.133	8	20.452	0.176	0.548
4	24	0.018 8	10	20.083	0.257	0.767
4	29	0.264	5	19.966	0.125	0.272

TABLE 2. Regression analysis* for superficial corn moisture content (MCX) determined by the air-oven method vs. humidity ratio (W) of the drying air

Lot	Estimate of Parameters†: BO (%)	Standard Deviation for BO (%)	B1 (%)	Standard Deviation for B1 (%)	R^2
1	16.474	0.195	−60.630	15.282	0.5477
2	19.340	0.207	−58.896	16.310	0.5008
3	24.270	0.227	−48.648	17.800	0.3161
4	20.661	0.067	−24.459	4.568	0.4116

* Model is: MCX = BO + B1 * W

† All estimates are significant for P = 0.05.

TABLE 3. Estimates of actual corn moisture contents (MCO) and apparent final moisture contents (X) of corn dried by the air-oven procedure

Part A: MCO estimates

Lot	MCO (% d.b.)	Standard Deviation of MCO (% d.b.)
1	15.655	0.101
2	18.547	0.137
3	23.621	0.137
4	20.532	0.129

Part B: X Estimates

Humidity Ratio W (g water/g dry air)	X (% d.b.)	Standard deviation of X (% d.b.)	Probability* P
0.000 0	0.000 00	(assumed value)	—
0.009 2	0.039 86	0 071 07	0.576 9
0.024 4	0 066 19	0.081 74	0 421 0
0.018 8	0.266 26	0.071 25	0.000 4
0.026 4	0.471 40	0.094 76	0.000 1

* P is the probability of obtaining the listed value of X if the null hypothesis, H_o : X = 0, is true.

0.018 8 and 0.026 4 were significantly different from zero (P = 0.000 5).

An equation relating apparent final moisture content of corn to humidity ratio was determined. Linear regression was used to fit several polynomial models to the data in Table 3, Part B. The simplest model that accurately fitted the data was

$$X = 673.8 * W^2 \quad [6]$$

where X is the apparent final moisture content (%db) and W is the humidity ratio (g water per g dry air).

Equation [6] represented the data with an R-square of 0.987. The coefficient, 673.8, was significant at P = 0.000 5.

DISCUSSION

These results show that the apparent final moisture content for corn tested with the air-oven procedure depends on the humidity ratio of air entering the oven. In some situations, the resulting deviations in superficial corn moisture content can be important. When the apparent final moisture content was not zero, the oven procedure left more water in the sample than was needed to offset nonaqueous losses. The calculated or superficial corn moisture content, MCX, was less than the actual corn moisture content, MCO. A relationship between MCX, MCO, and X was developed and presented in equation [4].

Equations [4] and [6] together can be used to correct oven-determined superficial corn moisture values (%db) for any level of humidity ratio between 0.0 and 0.0264 (g water per g dry air). Substitution of equation [6] into equation [4] yields

$$MC0 = MCX + (673.8 * W^2) * (MCX + 100)/100 \quad [7]$$

Many people prefer to work with wet basis moisture content. For convenience, equation [8] expresses the relationship of equation [7] in terms of wet-basis moisture content

$$MCOWB = 100 - 100 * (100 - MCXWB)/(100 + 673.8 * W^2) \quad [8]$$

where

MCOWB = actual moisture content (% wb) for X = 0,
MCXWB = superficial corn moisture content (% wb) corresponding to X,
W = humidity ratio (g water per g dry air).

Figure 2 shows correction factors for several values of superficial corn moisture content (% wb) over a range of humidity ratios. The factors, obtained by use of equation [8], can be multiplied times oven-determined superficial corn moisture contents, MCXWB, to obtain estimates of actual values, MCOWB. At humidity ratios below 0.012, the correction factors obtained from Fig. 2 are less than 1.01 for the range of superficial corn moisture contents listed on the figure. For humidity ratios below 0.004,

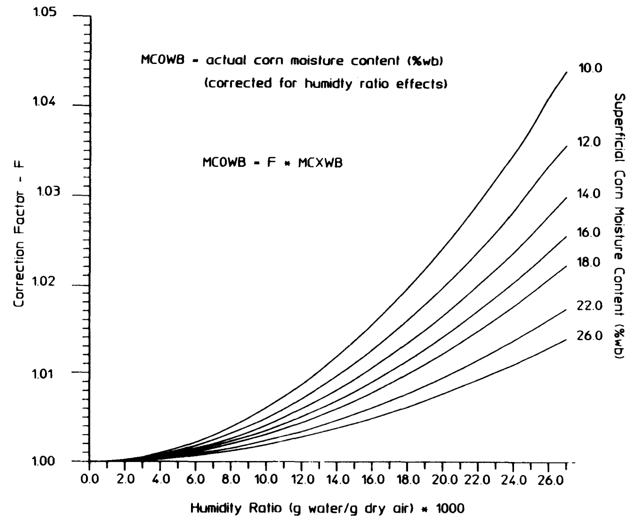

Fig. 2—Factors for changing corn moisture contents measured by the 72-hour, 103° C air-oven procedure to moisture content values corrected for air humidity effects.

correction factors are less than 1.001. Thus, for low humidity ratios, deviation of apparent moisture content from actual moisture content is negligible; but for air conditions typical in many regions of the United States, superficial corn moisture contents can deviate appreciably from actual values. Two examples will illustrate the magnitude of error possible.

At average laboratory air conditions of 26° C (78° F)and 90% relative humidity, conditions not uncommon in humid areas, the corresponding humidity ratio would be 0.018 8. Under these air conditions, suppose the superficial corn moisture content of a sample is observed to be 17.5% db (14.9% wb). Equation [7] indicates the actual dry-basis moisture content is 17.8%. Actual wet-basis moisture content given by equation [8] is 15.1%.

If humidity ratio was 0.0264 (corresponding to a temperature of 33° C (92° F) and a relative humidity of 90%, for example), the actual moisture content for this corn sample would be 18.1% db by equation [7] and 15.3% wb by equation [8]. Figure 2 can be used as an alternative to equation [8]; a correction factor can be found to adjust the superficial corn moisture content (%wb) to the actual value. For a humidity ratio of 0.0264 and an superficial corn moisture content of 14.9% wb, a correction factor of 1.026 is obtained. Thus, the actual wet basis moisture content would be

$$\begin{aligned} MCOWB &= 1.026 * 14.9\% \\ &= 15.3\% \end{aligned}$$

For some purposes, errors of this magnitude can be significant. In winter months or in air conditioned laboratories, the humidity ratio is low and deviation of superficial corn moisture contents from actual values is small. However, the error can be significant for hot, humid test conditions.

CONCLUSIONS

1. Humidity ratio had a statistically significant effect on superficial corn moisture content as determined by the air-oven procedure.

2. Apparent final moisture content of corn dried in the air-oven was found to increase as a quadratic function of humidity ratio of the drying air.

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